CSIRO PUBLISHING

International Journal of Wildland Fire **2020**, *29*, 215–228
https://doi.org/10.1071/WF19092

Standing dead trees contribute significantly to carbon budgets in Australian savannas

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Abstract. Previous estimates of greenhouse gas emissions from Australian savanna fires have incorporated on-ground dead wood but ignored standing dead trees. However, research from eucalypt woodlands in southern Queensland has shown that the two pools of dead wood burn at similar rates. New field data from semiarid savannas across northern Australia confirmed that standing dead trees comprise about four times the mass of on-ground dead wood. Further, the proportion of total woody biomass comprising dead wood increases with decreasing fire frequency and a decreasing proportion of late dry season (August to December) fires. This gives scope for increasing the carbon stock in the dead wood pool with a reduced fire frequency. Following a previously published approach to quantify total dead wood loads in savannas, new and previously collected data on tree stand structures were used across the whole savanna zone to quantify dead wood loads in equilibrium with historic fire regimes. New parameters are presented for calculating dead wood dynamics including dead trees in Australia's savannas.

Additional keywords: burning, dead wood, fire, greenhouse, woodland.

Received 19 June 2019, accepted 21 December 2019, published online 6 February 2020

Introduction

Understanding fluxes of carbon and greenhouse gases through terrestrial systems is critical for quantifying global atmospheric dynamics. Tropical savannas cover 20% of the globe and have a high anthropogenic component to their carbon flux through the management of frequent fires in areas with little grazing of domestic livestock (van Leeuwen *et al.* 2014; Williams *et al.* 2017), and less frequent fires in areas of moderate to heavy grazing. Savanna fires contribute 5.6% of global biomass burning emissions. In Australia, savannas cover 25% the continent and their fires contribute 15% of the global burnt area (van der Werf *et al.* 2006; Williams *et al.* 2017). Within Australia, savanna fires account for 2–4% of the currently accountable greenhouse gas emissions (Cook and Meyer 2009). In much of the savanna zone, depopulation as a result of colonisation has led to an increase in the frequency and severity of fires (Ritchie 2009; Russell-Smith *et al.* 2013). Although much work has examined the role of fire in the dynamics of live tree populations in Australia's tropical savanna, a recent review concluded that these tree stands were more likely to be water limited than fire limited (Murphy *et al.* 2015).

Australia has international obligations to account for and to reduce its net greenhouse gas emissions. There is thus a need for a national-scale emissions inventory and for schemes to reduce emissions where possible (Commonwealth of Australia 2017). The latter have led to the development of a fire management industry in the savannas of northern Australia supported by carbon credits gained through emissions reductions. Both the inventory and the emissions reductions schemes require continued improvement through scientific advances. Fuel dynamics in the savanna zone is an area where there has been limited knowledge and consequently has contributed substantial uncertainty to the emissions accounts.

The first quantification of emissions from savanna fires in Australia was by Hurst *et al.* (1994). This work focused on emissions from the fine fuel bed. The emission factors were measured on smoke samples from elevated plumes collected using aircraft-based sampling techniques. Smoke sampled in this way is produced mainly at the fire front from flaming combustion of fine fuels, with a small contribution from smouldering of those fuels after the fire front has passed. In their calculations, (Hurst *et al.* 1994) did not include emission factors specifically from dead wood, nor estimates of dead wood loads.

Quantifying dead wood loads is critical to robust estimates of emissions for two reasons. First, dead wood is a significant fraction of the total fuel load in most Australian savanna vegetation and to ignore it will underestimate total emissions. Second, emissions of methane from dead wood combustion are typically ~10 times greater per unit of fuel consumed than from fine fuels (Meyer and Cook 2015). Consequently, most of the more recent inventory accounting methodologies use a stratified or book-keeping accounting approach that separates fuels into classes such as fine fuels, on-ground dead wood and standing dead trees (IPCC 2006; Prichard *et al.* 2006; Commonwealth of Australia 2017).

Two estimates of dead wood pools in northern Australia have been published for inventory analyses (Russell-Smith *et al.* 2009; Yates *et al.* 2015), but these only measured dead wood on the ground. Other regional studies considered only the standing dead trees without the on-ground dead wood (Burrows *et al.* 2002; Fensham 2005; Bray *et al.* 2006). Few studies have considered both on-ground and standing dead wood in Australia's tropical savannas (but see Bray *et al.* 2014; Hunt 2014). These studies indicate that standing dead trees constitute up to 11% of total live and dead standing wood load in savanna systems, and thus their inclusion is likely to make a significant contribution to carbon budgets.

Quantifying the changes in emissions as a result of changed fire regimes requires estimates of fuel loads based on fuel accumulation curves (Cook and Meyer 2009). Cook *et al.* (2016) developed a mass balance approach consistent with the 2006 IPCC guidelines to describe fuel accumulation in systems where fires are frequent. This approach explicitly accounts for fire patchiness or uniformity and combustion completeness, also known as burning efficiency, and is applied to both fine fuel (<6 mm diameter) and two classes of dead wood (coarse fraction 6–50 mm diameter and heavy fraction ≥50 mm diameter) in Australian high rainfall savannas.

Direct sampling of chronosequences by using space for time substitution is an alternative to developing fuel accumulation curves from a mass balance approach, taking account of gains and losses. For on-ground dead wood in the savannas of northern Australia, the inherent variability in these data was such that no significant trends with time since fire were detected in field data (Russell-Smith *et al.* 2009; Yates *et al.* 2015). This is to be expected given the demonstrated shortcomings of the chronosequence approach (Johnson and Miyanishi 2008). As discussed by Cook *et al.* (2016), with respect to fuel accumulation there is an important difference between being unable to detect a trend and concluding that there is no trend. Since it is known that dead wood is consumed during fire events and is replaced more slowly through deposition between fire events, there must be an accumulation curve for dead wood. Accordingly, Cook *et al.* (2016) developed an approach to estimate annual inputs to the dead wood pool and its decomposition so that fuel accumulation curves could be produced using a mass balance approach. The annual input of dead wood was calculated as the product of the annual tree mortality rate, and the live tree biomass coupled with estimates of branch fall from live trees. These values were derived from data on tree stand structures and mean growth rates. Annual losses of dead wood were determined from data describing the fire regime, combustion efficiency and biological decomposition rates. The estimates of emissions and carbon dynamics under various fire regimes that were calculated by this approach were thereby based on an explicit modelling of the underlying processes.

The present study aims to (1) provide insights into the importance of standing dead trees to the carbon dynamics of frequently burnt Australian savannas, and (2) to develop new dead wood input parameters for the Australian Government's Savanna Technical Guidance document that supports the Savanna fire management 2018 (Sequestration and Emissions Avoidance) Methodology Determination. This work will continue to improve the quantification of savanna burning emissions and carbon dynamics in Australia's savannas, and will support improved fire management.

Methods

Overview

New Australian Government legislation aiming to support emissions reduction and carbon sequestration through improved fire management in savannas (herein called the 'savanna burning methodology') includes an equation to calculate fuel loads in equilibrium with particular fire regimes (Commonwealth of Australia 2018: eqn 11). This equation is equivalent to eqn 15 of Cook *et al.* (2016). The fuel loads are a function of annual inputs (L), decomposition rates (k), the frequency of early and late dry season fires, the patchiness of those fires and the burning efficiency of particular size classes of fuel under those fires. This legislation invokes a table of input values for different fuel classes in different vegetation types that is given in a subsidiary document (section 4.3 in Australian Government 2018). Nine vegetation types are defined across northern Australian and were derived by Meyer *et al.* (2015) using data of Thackway *et al.* (2014) (Fig. 1; Appendix 1). For coarse and heavy fraction dead wood, these input values were scaled to fit field observations of on-ground dead wood presented by Russell-Smith *et al.* (2009) and Yates *et al.* (2015), because they were the only data available at the time (Meyer *et al.* 2015). Here we collate existing data and describe the collection of new data to enable the calculation of new values of dead wood inputs that will include both standing and on-ground dead wood. We use these data to explore the dynamics of dead wood in frequently burnt Australian savannas.

Calculation of dead wood dynamics

The mathematical approach is presented in detail in Cook *et al.* (2016); here we describe how we applied that approach in the present study.

The fuel accumulation equation of Olson (1963) describes the rate of fuel accumulation, $d\Phi/dt$, in terms of the input of dead organic matter L and the biological decomposition rate k:

$$\frac{d\Phi}{dt} = L - k\Phi \quad (1)$$

Raison *et al.* (1983) modified this approach to allow for the inclusion of post-fire residue because dead wood of any fraction is rarely completely consumed in a fire event. An example solution to this model is shown in Fig. 2 for the heavy fraction, with the maximum fuel load being equal to L/k and showing values for the mean post fire fuel load (Φ_0), the mean fuel load over space and time ($\overline{\Phi}$) and the mean fuel load at the mean fire recurrence interval (Φ_r). We calculate these values using burning efficiency and fire patchiness data given by Cook *et al.* (2016) and Yates *et al.* (2015) for high rainfall and semiarid savannas respectively.

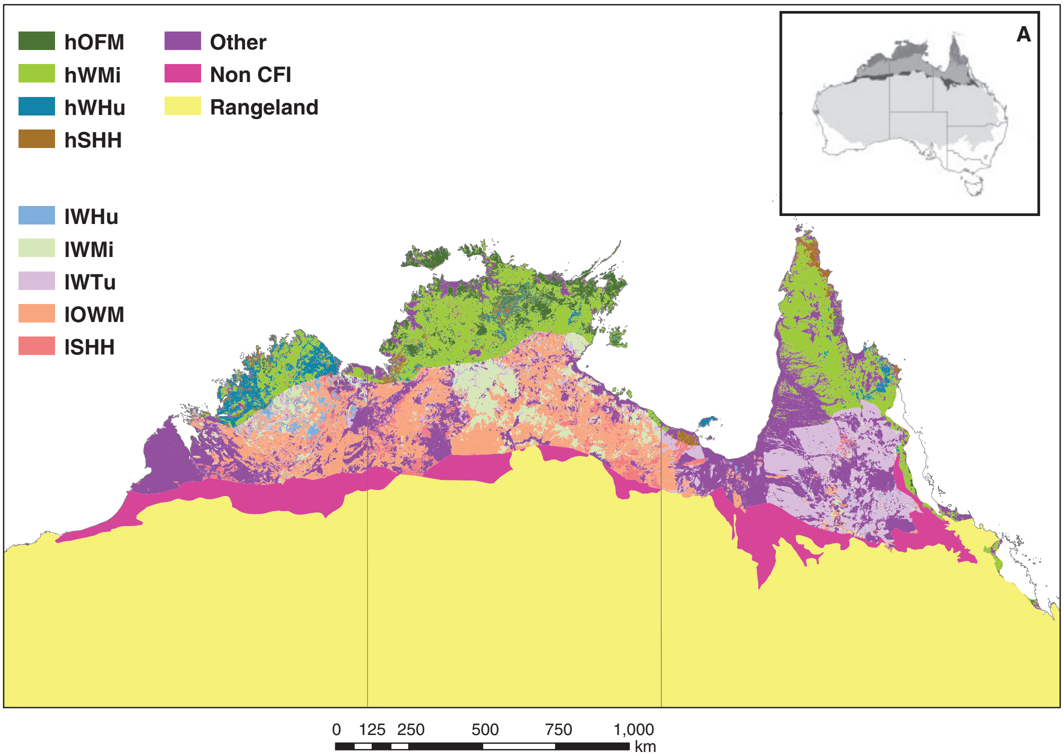

Fig. 1. A map of the vegetation types defined in the 'Savanna fire management 2018 (Sequestration and Emissions Avoidance) Methodology Determination', also showing excluded vegetation types.

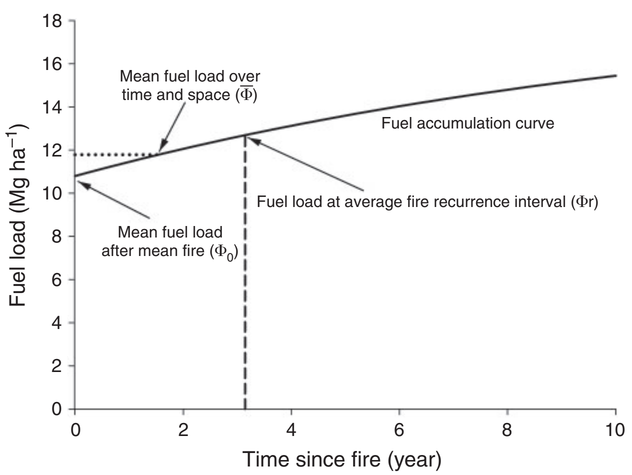

Fig. 2. Fuel accumulation curve for 'with-project' fire regime for heavy fraction of woody debris of *Eucalyptus* open forest for West Arnhem Land Fire Abatement project, as developed by Cook *et al.* (2016).

For woody debris, L is calculated from measured tree stand structures. This first requires parameterising the stand structures. A semi-log relationship between density of live stems ρ (ha^{-1}) and stem diameter D (m) appears to be general for describing Australian savanna tree stand structures, if a sufficiently large sample is measured (Hutley *et al.* 2011; Cook *et al.* 2016):

$$\rho(D) = \rho_0 e^{-\lambda D} \tag{2}$$

where ρ_0 is the y-axis intercept, which represents the nominal density of stems with a diameter at breast height (DBH; 1.3 m) of 0. This defines the density of small trees entering the sapling population. The slope, λ (m^{-1}), defines the relationship between stem density and stem size.

The input of on-ground coarse fraction dead wood L_c (Mg ha^{-1} $year^{-1}$) is mostly created by the fall of small branches from trees, and its annual production rate can be calculated by scaling against the total basal area of live trees A (m^2 ha^{-1}):

$$L_c = 0.023A \tag{3}$$

Expressed in terms of the stand structure parameters, this equation becomes

$$L_c = \frac{0.023\rho_0\pi}{2\lambda^3} \tag{4}$$

The death of trees is the dominant source of heavy fraction dead wood. Its annual production rate L_h (Mg ha^{-1} $year^{-1}$) can be calculated as the product of the live stand biomass M (Mg ha^{-1}) and the mean annual mortality rate (μ) from all causes, after adjusting for the proportion of leaves and twigs:

$$L_h = 0.948\mu M \tag{5}$$

If tree growth rate is expressed as the annual increment in stem diameter and is assumed to be independent of stem size (which has been demonstrated for trees in the region; Cook *et al.* 2016), tree mortality expressed as a proportion per year can be calculated from the stand structure and mean annual increment in stem diameter ($\overline{\Delta \mathrm{D}}$):

$$\mu = 1 - e^{-\overline{\Delta \mathrm{D}}\lambda} \tag{6}$$

Cook *et al.* (2015) showed that mean stem diameter increment did not vary with rainfall, so a constant value could be used to calculated tree mortality. The values of λ have already been determined for open forest and woodland savannas in high rainfall savannas (>1000 mm mean annual rainfall) by Cook *et al.* (2016). Here we determined the value of λ for woodland savannas in the semiarid savanna zone (600–1000 mm mean annual rainfall) using newly collected and collated data on tree stand structure in this region (see below). We lump all data collected from 60 sites of varying size across the region into one population for this analysis. Preliminary investigations of the new stand structure data and exploration of the equivalent data for high rainfall savannas indicated that the value of λ showed little systematic variation among sites, but values of ρ_0 (the *y*-axis intercept of the negative exponential curve of tree stand structure), which scales with total basal area (*A*) did vary among sites according to variation in rainfall and soil types.

Having obtained a value of λ and thus a mortality rate for semiarid woodlands, we calculated the values of annual inputs of coarse and heavy fraction dead wood across the savanna zone for the defined vegetation types. To do this, grid cells of $0.01° \times 0.01°$ were defined across the Australian savanna zone and allocated to one of the nine defined vegetation classes (Fig. 1; Appendix 1). These vegetation types were loosely defined on a range of floristic and structural attributes. In the present study, we also consider a tenth vegetation class, 'other', which contains a variety of vegetation communities (Meyer *et al.* 2015). For each grid cell, the total basal area of trees *A* ($\mathrm{m}^2\ \mathrm{ha}^{-1}$) was calculated following the approach of Cook *et al.* (2015) using the equation of Williams *et al.* (1996), which relates *A* to mean annual rainfall and soil surface clay content. We used rainfall data from the Australian Bureau of Meteorology (http://www.bom.gov.au, verified 14 January 2020) and soil data from the Australian Soil Resource Information System (http://www.asris.csiro.au, verified 14 January 2020). From *A* and λ, the mean value of the nominal density of stems of diameter 0 m, ρ_0, in each grid cell can be calculated (by reworking eqn 23 of Cook *et al.* 2016):

$$\rho_0 = \frac{2A\lambda^3}{\pi} \tag{7}$$

Further, we assume that value of λ from high rainfall woodlands can be applied to both woodland vegetation classes defined for this rainfall band, and the new value of λ from semiarid woodlands can be applied to all four woodland vegetation classes defined for the 600–1000-mm savannas.

With values of λ and ρ_0 for each grid cell, the biomass of live trees could then be calculated using the allometry of Paul *et al.* (2016). We used this allometry rather than that of Williams *et al.* (2005), which was used by Cook *et al.* (2016), because of the greater dataset that Paul *et al.* (2016) included and the simpler formulation of the allometric equation. Equation 3c of Paul *et al.* (2016) can be simplified by subsuming the required bias correction factor for this equation, with the relationship of biomass of an individual tree as a function of size ($M(D)$) expressed as

$$M(D) = 7.99D^{2.375} \tag{8}$$

By combining Eqns 2 and 8, the aboveground live biomass for a stand *M* ($\mathrm{Mg\ ha}^{-1}$) can be determined by the definite integral:

$$M = 7.99\rho_0 \int_0^{\infty} e^{-\lambda D} D^{2.375}\, dD \tag{9}$$

This is:

$$M = 7.99\rho_0 \frac{\Gamma(2.375+1)}{\lambda^{2.375+1}} \tag{10}$$

where Γ is the gamma function. Hence:

$$M = \frac{23.17\rho_0}{\lambda^{3.375}} \tag{11}$$

With the value of *M* calculated for each grid cell, the values of L_c and L_h were then calculated as described above (Eqns 4 and 5) and the mean values for each vegetation class determined.

Stand structure data for semiarid savannas

Existing data on live and dead standing trees (collected from 46 belt transects with a total area of 13.16 ha in semiarid savannas of Queensland as part of the Queensland Government's TRAPS program; Burrows *et al.* 2002) were supplemented with newly collected data across northern Australia. New data on tree stands were collected in 2016–17 at 14 sites at ~150-km intervals along the 800-mm rainfall isohyet from Queensland to Western Australia. At each site the diameter of every live or dead tree with a DBH (1.3 m) ≥0.05 m was measured and the species identified. Most trees were single stemmed but for multi-stemmed individuals where the stems arose below 1.3 m height, we measured the diameter of each stem. Trees were counted along transects with a width of 10–20 m and length of several hundred metres, depending on tree density. The total area sampled was 14.7 ha, with individual sites ranging from 0.2 to 2.0 ha. Thus, tree stand structures were compiled from 60 sites covering 27.86 ha across northern Australia with mean annual rainfall between 600 and 1000 mm. For each tree measured in the new plots, the health was rated on a 1–5 scale, with 1 having a completely healthy canopy and 5 being dead. For 10 of the newly collected sites, it was also possible to sample on-ground heavy-fraction dead wood; in others, tall grass obscured the ground and time constraints prohibited sampling of this pool. The length of each on-ground log (≥0.05 m diameter) that would have been rooted within the belt transects was recorded. The DBHs of those logs were estimated by measuring 1.3 m from the tree base at the expected original ground level. Because of time constraints, it was not possible to measure on-ground coarse fraction woody debris. In the absence of published allometries for dead trees, we assumed that their biomass-to-stem diameter had the same relationships as live trees. Although this is likely to overestimate mass of dead wood in dead trees, for the purpose of determining their relative contribution to total stand mass and to compare fallen with standing dead wood, it is a satisfactory assumption. The carbon balance determined from the annual production of dead wood will avoid these shortcomings because the passage of all parts of live trees into the dead pool will be included in the estimation.

Values of live tree wood mass, mortality rate and annual inputs of coarse and heavy dead wood were then calculated using a constant stem diameter increment rate of trees across the savanna zone (0.0025 m year^{-1}; Cook *et al.* 2015).

The frequency of early dry season (January to July) and late dry season (August to December) fires over 27 years was derived for each grid cell from the fire area dataset compiled by Landgate WA using AVHRR imagery (https://firewatch-pro.landgate.wa.gov.au/home.php, accessed September 2017). Together with the values of L_c and L_h, and an estimate of decomposition rate, these data enable us to calculate the mean dead wood stock.

The annual inputs of coarse and heavy dead wood, total dead wood stock, total basal area, live tree biomass and the density of trees with a diameter >0.05 m were calculated for each grid cell. From these, we calculated the mean values for eight of the defined vegetation classes. For the two shrubland communities (high and low rainfall shrubland with hummock grasses, hSHH and lSHH respectively; Fig. 1), the dominant stratum was shrubs <5 m tall with at most, sparse tree cover (Commonwealth of Australia 2015; Lynch *et al.* 2015; Appendix 1); therefore the biomass of live trees was low, highly spatially variable and difficult to quantify. For these two vegetation classes, the annual inputs of dead wood were not calculated.

Estimating wood decomposition rate

Cook *et al.* (2016) estimated a wood decomposition rate (0.083 year^{-1}) for savannas in high rainfall (>1000 mm) location in the Northern Territory based on consideration of annual inputs of coarse-fraction woody debris and measured on-ground debris loads. Following further considerations, a value of 0.09 year^{-1} was given as the value in the supporting document to the savanna burning methodology (Australian Government 2018). Nevertheless, there are no published direct measurements of wood decomposition rates in northern Australian savannas. To provide a field estimate, pieces of wood of ~0.05 m diameter were collected from dead *Eucalyptus* trees in the Darwin region, cut to ~0.3 m lengths and weighed. These were tagged and placed on the ground in the field at Victoria River Research Station (130°54′E, 16°06′S; ~750 mm mean annual rainfall) in March 2016 and collected in April 2018. Mean annual decomposition rates k (year^{-1}) were calculated for each piece of wood as

$$k = Ln((Initial\ weight - Final\ weight)/Initial\ weight)/t \quad (12)$$

where t is the number of years of decay.

Results

Stand structures

The aggregated stand structure data from the tree plots in the semiarid savanna sites (600–1000 mm) was well described by a negative exponential curve, and the cumulative distribution function was fitted to the aggregated stand structure data to determine λ (Fig. 3). The calculated mean density of stems with DBH >0.05 m was 235 stems ha^{-1}, and the value of λ from the cumulative distribution function was 9.05 m^{-1}. Together, these allow for the calculation of ρ_0 and other structural attributes averaged for sites sampled in these semiarid woodlands (Table 1). These are compared in the table with values previously determined in high rainfall open forests and woodlands. The woodlands in the high rainfall zone have similar total basal area and biomass to semiarid woodlands.

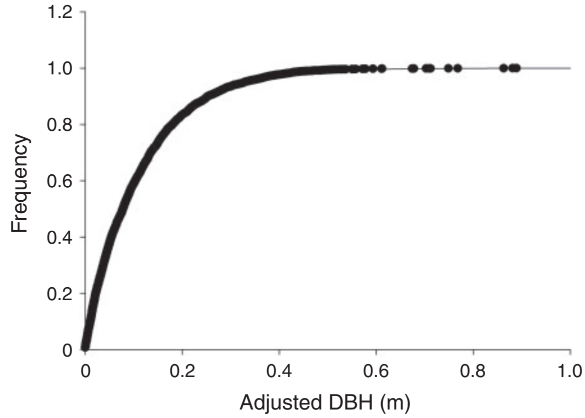

Fig. 3. Cumulative distribution of tree stems >0.05 m DBH (diameter at breast height) across 60 plots with a total area of 27.855 ha in Australian semiarid savannas (600–1000 mm rainfall). The *x*-axis has been adjusted by subtracting 0.05 m from DBH to support curve fitting. $Y = 1 - e(-9.05(\mathrm{DBH} - 0.05))$ $r^2 = 0.9996$.

Relative contribution of dead wood to total wood biomass

Heavy-fraction dead wood comprised ~12% of the total woody biomass across the 10 sites (6.6 ha) in low rainfall savannas for which live, standing dead and on-ground dead wood pools in the heavy fraction were measured (Table 2). Of that dead wood, ~79% of the biomass comprised standing dead trees, with the rest being on-ground dead trees (Table 2).

Drivers of dead wood gains

Across northern Australia's savannas there were ~23 × 10^9 live trees with a D >0.05 m, with a total aboveground live biomass of 3.6 Pg (Table 3). Of the defined vegetation classes, the high rainfall woodlands with mixed grass understorey (hWMi) dominated the stem count and the biomass, owing to both the substantial area of this class and its high mean total basal area.

Annual production of dead wood was dominated by the heavy fraction that ranged among the vegetation classes from 0.56 to 1.16 Mg ha^{-1} year^{-1} (Table 4), whereas values for the coarse fraction dead wood ranged from 0.09 to 0.18 Mg ha^{-1} year^{-1}.

Drivers of dead wood losses: decomposition and fire regimes

Decomposition rates of the wood samples varied considerably, with the greatest rate (1.41 year^{-1}) being more than 50 times the lowest (0.026 year^{-1}). The rates appeared to fall into

Table 1. Structural properties of measured woodlands and open forest savannas in northern Australia
For the >1000-mm zone, the structural attributes are taken from Cook *et al.* (2016)

Stand structure attribute	Rainfall zone		
	600–1000 mm	>1000 mm	
	Woodland	Woodland	Open forest
λ (m^{-1})	9.0500	10.800	8.7000
ρ_0 (stems ha^{-1} m^{-1})	3349.0000	5818.000	4817.0000
$\rho_{>0.05\,m}$ (stems ha^{-1})	235.0000	315.000	358.0000
Total basal area (m^2 ha^{-1})	7.1000	7.300	11.5000
Live biomass (Mg ha^{-1})	45.8000	44.100	75.3000
Mortality (μ: $year^{-1}$)	0.0224	0.027	0.0215
Heavy woody debris production (L: Mg ha^{-1} $year^{-1}$)	1.0300	1.170	1.6200
Coarse woody debris production (L: Mg ha^{-1} $year^{-1}$)	0.1600	0.170	0.2600

Table 2. The mean amount of live standing trees, dead standing and dead on-ground wood (heavy fraction) in 10 plots comprising 7.2 ha across northern Australia

Pool of wood	Biomass (Mg ha^{-1})	Total basal area (m^2 ha^{-1})	Density of stems >0.05 m diameter (ha^{-1})
Live standing	29.2	5.10	303.2
Dead standing[A]	3.1	0.59	47.6
Dead on-ground[A]	0.8	0.13	4.6

[A]Calculated from log diameter equivalent to diameter at breast height.

Table 3. The area of each vegetation class and estimated total number and biomass of live trees with a diameter at breast height (DBH) >0.5 m, for count and mean total basal area of live trees in each vegetation class
hOFMi, high rainfall open forest with mixed grasses; hWMi, high rainfall woodlands with mixed grass; hWHu, high rainfall woodland with hummock grasses; hSHH, high rainfall shrubland with hummock grasses; lWHu, semiarid rainfall woodland with hummock grasses; lWMi, semiarid rainfall woodland with mixed grasses; lWTu, semiarid woodland with tussock grasses; lOWmi, semiarid open woodland with mixed grass; lSHH, semiarid shrubland with hummock grasses; –, no data

Vegetation class	Area ('000 km^2)	Number of live trees of DBH >0.05 m ($\times 10^6$)	Mass of live trees (Tg)	Mean total basal area (m^2 ha^{-1})
hOFMi	69.2	1666	350	7.7
hWMi	226.0	7041	984	7.2
hWHu	41.8	1258	176	7.0
hSHH	–	–	–	–
lWHu	16.6	275	54	5.0
lWMi	71.2	997	194	4.2
lWTu	119.5	1524	297	3.8
lOWMi	214.2	2898	564	4.1
ISHH	–	–	–	–
Other	355.6	7210	1007	4.7
Total		22 900	3625	

three populations (Fig. 4), with the largest proportion (64%) of wood samples having a mean value of 0.087 $year^{-1}$ and the other populations having faster decomposition rates. Decomposition rates declined significantly with increasing wood density (Fig. 5), but no trends could be detected with diameter, most likely owing to the small range of diameters included in this study.

The mean frequency of all fires (1988–2015) in the 10 vegetation classes considered in northern Australia varied from 0.17 to 0.36 $year^{-1}$, with Emissions Reduction Fund (ERF) project areas within each vegetation class having greater fire frequencies (0.26 to 0.37 $year^{-1}$; Table 5). The mean frequencies of late dry season fires historically ranged from 0.12 to 0.22 $year^{-1}$ and up to 0.26 $year^{-1}$ in ERF project areas. Across Australia, fire frequency is greater in the north (Fig. 6*a*), with early dry season fires dominating in the north-western part of the Northern Territory (Fig. 6*b*), and late dry season fires dominating in the northern Kimberley region of Western Australia, north-eastern Northern Territory and western side of Cape York Peninsula in Queensland (Fig. 6*c*).

Table 4. Values of annual inputs of coarse (L_c) and heavy (L_h) woody debris in defined vegetation classes across northern Australia's savannas as listed in the National Inventory Report (NIR) (Meyer *et al.* 2015) and as calculated herein

hOFMi, high rainfall open forest with mixed grasses; hWMi, high rainfall woodlands with mixed grass; hWHu, high rainfall woodland with hummock grasses; hSHH, high rainfall shrubland with hummock grasses; lWHu, semiarid rainfall woodland with hummock grasses; lWMi, semiarid rainfall woodland with mixed grasses; lWTu, semiarid woodland with tussock grasses; lOWmi, semiarid open woodland with mixed grass; lSHH, semiarid shrubland with hummock grasses; –, no data

Vegetation class	Annual inputs of dead wood (Mg ha^{-1} year^{-1})			
	L_c		L_h	
	NIR	This study	NIR	This study
hOFMi	0.25	0.18	0.5650	1.09
hWMi	0.2175	0.17	0.3392	1.16
hWHu	0.2924	0.16	0.8879	1.12
hSHH	0.0704	–	0.3423	–
lWHu	0.2677	0.12	0.1093	0.72
lWMi	0.1437	0.10	0.2504	0.61
lWTu	0.2434	0.09	0.1941	0.56
lOWMi	0.1446	0.09	0.0946	0.59
lSHH	0.0871	–	0.0375	–
Other	0.2175	0.11	0.3392	0.75

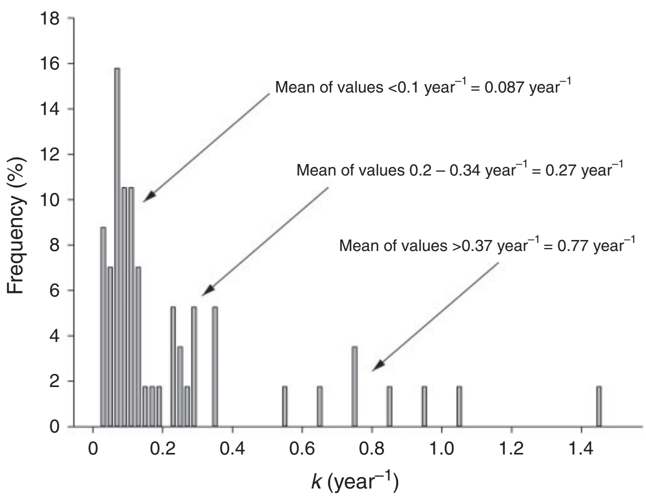

Fig. 4. The proportions of wood samples with various decomposition rates measured in a semiarid savanna over 2 years. The *x*-axis values are the mean of each bin with a 0.02 range.

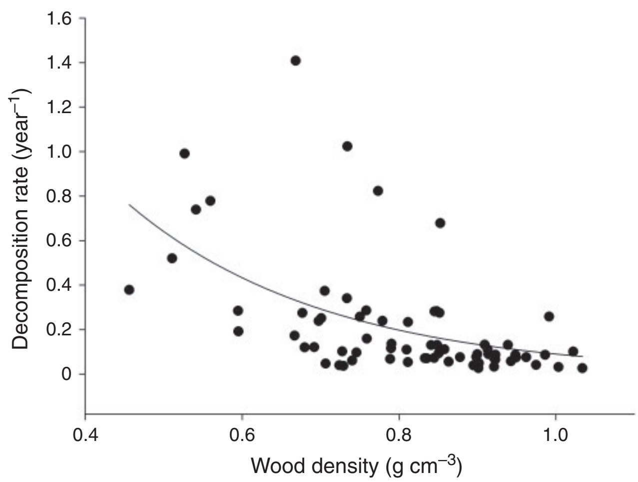

Fig. 5. The relationship between the decomposition rate of wood samples of 2.2–6.5 cm diameter and their density.

Dead wood stocks

The estimated total biomass of dead wood under baseline fire regimes (1988–2015), assuming a wood decomposition rate of 0.083 year^{-1} (Cook *et al.* 2016), ranged from 6.4 to 8.6 Mg ha^{-1} across the various vegetation classes (Table 6). The spatial distribution of dead wood under historic fire regimes is shown in Fig. 7. In the high rainfall savannas, the estimated mean dead wood averaged 58% of the mean maximum possible at long periods without fire; in the semiarid savannas, this value was 79%.

Discussion

The present study addresses two parameters that describe dead wood accumulation. These are the annual inputs and the decomposition rates. The mean load after the mean fire is dependent on both these parameters and the fire regime. For dead wood, the values of the annual inputs are largely driven by live tree stand structure. We found that for coarse fuels, the values of L_c determined here were lower than those calculated by fitting an accumulation model to field observations of fuel loads (Meyer *et al.* 2015). In this case, the discrepancy is likely owing to both inaccuracies and biases associated with field sampling using a chronosequence approach and to the large spatial and temporal variability in coarse fuel deposition, and consequently a low confidence in the assigned coefficient used to calculate L_c from total basal area. This issue was highlighted by Cuff and Brocklehurst (2015) in their description of the data collection underpinning our parameterisation. Targeted sampling of the on-ground coarse fraction, further measurements of inputs of this fraction from branch fall and partitioning of live tree wood into diameter classes would all increase the accuracy

Table 5. The mean frequency (1988–2015) of early (before 1 August), late and all fires in 10 vegetation classes across the savanna biome of northern Australia and in Emissions Reduction Fund project areas in each vegetation class

hOFMi, high rainfall open forest with mixed grasses; hWMi, high rainfall woodlands with mixed grass; hWHu, high rainfall woodland with hummock grasses; hSHH, high rainfall shrubland with hummock grasses; lWHu, semiarid rainfall woodland with hummock grasses; lWMi, semiarid rainfall woodland with mixed grasses; lWTu, semiarid woodland with tussock grasses; lOWmi, semiarid open woodland with mixed grass; lSHH, semiarid shrubland with hummock grasses

Vegetation class	Fire frequency ($year^{-1}$)					
	Early		Late		Total	
	All	Projects	All	Projects	All	Projects
hOFMi	0.081	0.134	0.185	0.227	0.266	0.361
hWMi	0.140	0.111	0.222	0.261	0.362	0.372
hWHu	0.115	0.128	0.188	0.226	0.303	0.353
hSHH	0.109	0.119	0.143	0.240	0.252	0.359
lWHu	0.115	0.129	0.186	0.218	0.302	0.347
lWMi	0.075	0.112	0.175	0.243	0.250	0.355
lWTu	0.027	0.073	0.131	0.189	0.158	0.262
lOWMi	0.075	0.121	0.159	0.211	0.234	0.332
ISHH	0.077	0.123	0.136	0.196	0.213	0.318
Other	0.048	0.109	0.119	0.209	0.166	0.317

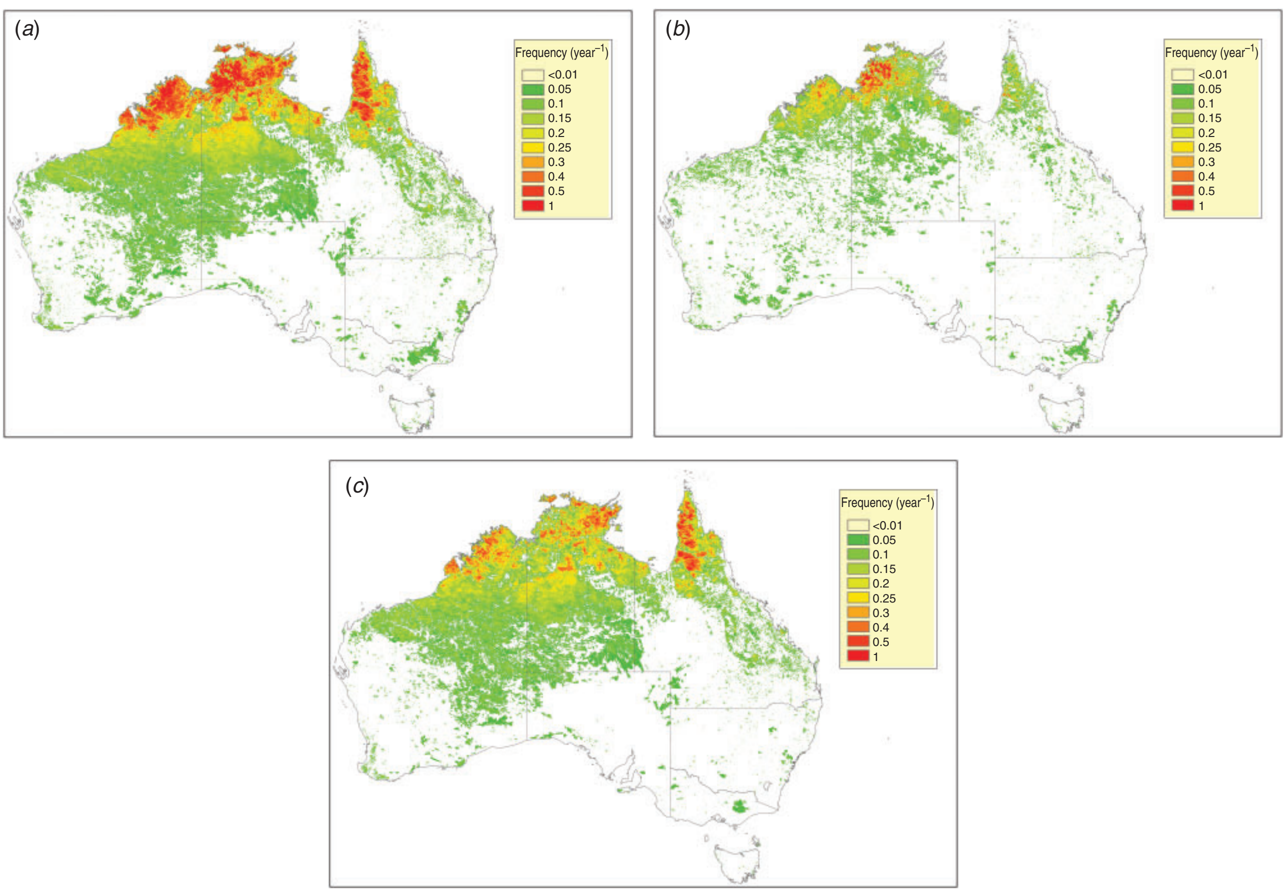

Fig. 6. The frequency of (*a*) all fires, (*b*) pre-August fires and (*c*) post-July fires across Australia, based on 28 years of fire scar data (Landgate).

Table 6. Estimates of dead wood biomass (both coarse and heavy) in north Australian vegetation classes based on either field observations of on-ground dead wood alone, or on mass balance modelling of dead wood dynamics including on-ground and standing pools based on knowledge of vegetation structure and past fire regimes

The values of the temporal and spatial mean ($\overline{\Phi}$) and of the mean post-fire residue ($\overline{\Phi}(0)$) are given for the baseline fire regime derived from 27 years of fire history (1988–2015). hOFMi, high rainfall open forest with mixed grasses; hWMi, high rainfall woodlands with mixed grass; hWHu, high rainfall woodland with hummock grasses; hSHH, high rainfall shrubland with hummock grasses; lWHu, semiarid rainfall woodland with hummock grasses; lWMi, semiarid rainfall woodland with mixed grasses; lWTu, semiarid woodland with tussock grasses; lOWmi, semiarid open woodland with mixed grass; lSHH, semiarid shrubland with hummock grasses; –, no data

Vegetation class	Woody debris load (Mg ha^{-1})			
	On-ground only (field observations[A])	Temporal and spatial mean on-ground and standing ($\overline{\Phi}$)	Mean post-fire on-ground and standing ($\overline{\Phi}(0)$)	Mean maximum
hOFMi	6.20	8.47	7.22	15.0
hWMi	3.10	8.27	7.11	15.9
hWHu	4.60	8.56	7.39	15.5
hSHH	2.30	–	–	–
lWHu	3.00	7.53	7.13	10.1
lWMi	2.71	6.56	6.19	8.50
lWTu	2.64	6.41	5.96	7.80
lOWMi	1.56	6.44	6.08	8.20
lSHH	0.90	–	–	–
Other	–	6.89	6.42	8.40

[A]Russell-Smith *et al.* (2009), Yates *et al.* (2015).

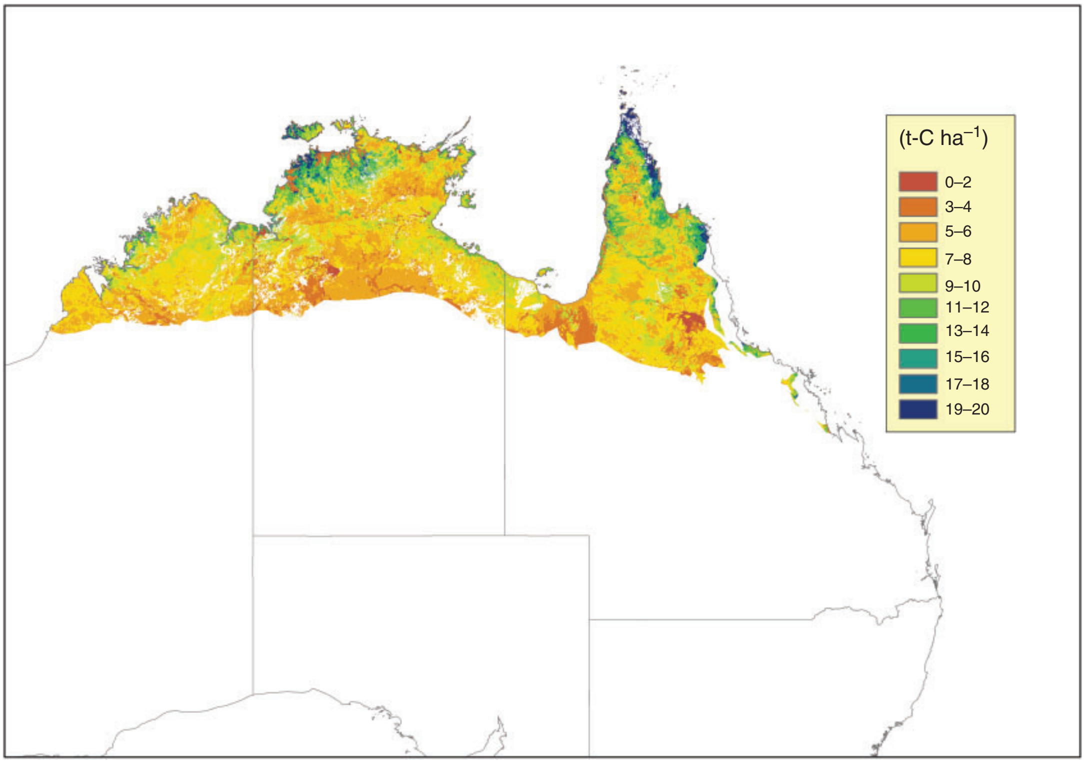

Fig. 7. The stock of both coarse and heavy wood debris (standing and on-ground) expressed as tonnes of carbon per hectare (t C ha^{-1}) under 1988–2015 fire regimes in the savanna zone across northern Australia.

of quantification of the dynamics of this fraction. However, its contribution to carbon dynamics is much less than for heavy fraction dead wood.

In contrast to the coarse fraction dead wood, the estimated mean annual production of heavy-fraction dead wood (on-ground and standing dead) was substantially greater than previous estimates that only considered the on-ground component of dead wood. The increases ranged from ~26% to nearly seven times. This is mainly owing to the exclusion of standing dead wood in the field observations, but would also be a result of the inherent difficulty in accurately measuring heavy fraction dead wood in the field. The new field observations reported here showed that standing dead wood was nearly four times the amount of on-ground dead wood. Although both values may be slightly overestimated because of the application of live-tree allometry, the relative differences remain – and the conclusion that excluding standing dead trees from previous estimates of dead wood represents a major data gap remains supported.

Fires late in the dry season dominate the fire regime in all vegetation classes throughout Australia's tropical savannas. Such fires typically occur during times when controlled burning is not permitted. Fire management usually aims to prevent such fires because of their large size, high intensity, smoke generation and risks to infrastructure and natural assets (Andersen *et al.* 2005; Yates *et al.* 2008). Improved fire management could reduce the frequency of late fires, and of fires overall, with potential reductions in greenhouse gas emissions. With incentives from carbon credits under the Australian ERF, such improvements are being achieved across increasing areas of northern Australia, while still maintaining fire as part of the landscape (Cook *et al.* 2012; Russell-Smith *et al.* 2013). The areas in which ERF projects have been established had a greater frequency of all fires, and of late dry season fires historically, than the overall means across northern Australia. That is, improved fire management under the ERF schemes is focused on areas with more uncontrolled fire regimes over the past few decades. One consequence of changing the fire regimes is that the fuel accumulation curves will change; the model of Cook *et al.* (2016) applied here will facilitate their revision when necessary.

The values of the wood decomposition rates estimated by inverse modelling previously (0.083 year^{-1}; Cook *et al.* 2016), and used in the calculations under the savanna burning methodology (0.09 year^{-1}; Australian Government 2018), are close to that of the mean of field measurements presented here for the most slowly decomposing pool. Mackensen *et al.* (2003) describe the complex phenomenon of wood decomposition in forests and the importance of quantifying rates, but also the difficulty of doing so. The significant relationship of decomposition rate with wood density indicates that the higher decomposition rates observed in about one-third of the wood samples should not apply to the much denser wood that constitutes the bulk of the biomass of most Australian savanna trees. These high rates are probably associated with unlignified wood. From this relationship, the decomposition rates used herein for calculations of woody fuel dynamics (0.083 year^{-1}), and that invoked by the savanna burning methodology (0.09 year^{-1}), are expected values for wood of density 0.91 and 0.89 g cm^{-3} respectively. Values of wood density for a range of savanna eucalypts range from 0.85 to 1.2 g cm^{-3} (Boland *et al.* 1984). Thus, the new data indicate that these previous estimates of dead wood decomposition rate were reasonable, and we do not recommend any changes at present. Nevertheless, it is clear that there is high variation in wood decomposition rates. The results presented here should be considered preliminary data, and there is a need for further studies in the northern savannas.

The field observations of on-ground dead wood (>6 mm) reported by Russell-Smith *et al.* (2009) and Yates *et al.* (2015) (Table 6) in all cases are substantially less than the estimates of the mean total dead wood, both on-ground and standing, calculated by process-based modelling from stand structure data. The difference was least for the high rainfall open forest with mixed grass (hOFMi), and greatest for the semiarid open woodland with mixed grass (lOWmi). In this open woodland, the on-ground dead wood load presented by Yates *et al.* (2015) was only 24% of our estimate of the total dead wood, and across all four semiarid systems, the mean area-weighted on-ground dead wood was 33% of modelled total dead wood load.

The direct measurements of both standing and on-ground dead wood (Table 2) confirmed that standing dead wood comprised most of the woody debris pool. Furthermore, the proportion of total woody biomass comprising dead wood declined with increasing frequency of fires consistent with modelling predictions using a mass balance approach. Failure to include standing dead wood in previous estimates of fuel loads for calculating combustion emissions in northern Australia thus represents a major oversight. The disparity in dead wood estimates caused by ignoring standing dead wood is greater in high rainfall woodlands and the semiarid systems than in the high rainfall open forests. Standing dead wood in eucalypt woodlands is consumed in fires at burning efficiencies similar to those reported for on-ground woody debris in savannas (Fensham 2005; Russell-Smith *et al.* 2009). Because wood combustion is a strong source of methane emissions (Meyer *et al.* 2012; Meyer and Cook 2015), emissions from Australian savanna fires have therefore been underestimated historically.

Using the fuel accumulation curve, we have introduced dynamics into the estimates of dead wood loads, whereas previously it had been assumed that dead wood loads were unchanging over time (Russell-Smith *et al.* 2009; Yates *et al.* 2015). The proportion of total woody biomass comprising dead wood should decrease with increasing fire frequency and with an increasing proportion of late dry season fires. We have run the model using the fire regimes at each of the 10 field sites where we have observations of both standing and on-ground dead wood. The results show that with increasing fire frequency, there is a decline in the proportion of the total biomass comprising dead wood (Fig. 8). Furthermore, our field observations are consistent with the modelled data in both magnitude and trend. This dependence of the amount of dead wood on fire regime forms the basis of the ability to manage carbon stocks by managing fire regimes.

Conclusions

At the scales of major vegetation classes, Australia's tropical savannas have fire frequencies ranging from ~0.17 to 0.36 fires year^{-1}, with late dry season fires dominating in all cases. Emissions avoidance projects under Australia's ERF cover ~334 000 km^2 of northern Australia's savannas. Projects have been established in areas that historically have had more frequent fires, and more frequent late dry season fires, than the area overall. With the move to including carbon sequestration as well as emissions avoidance in ERF methodologies and in the National Inventory Report, it was important that fuel accumulation curves were robustly parameterised to produce valid

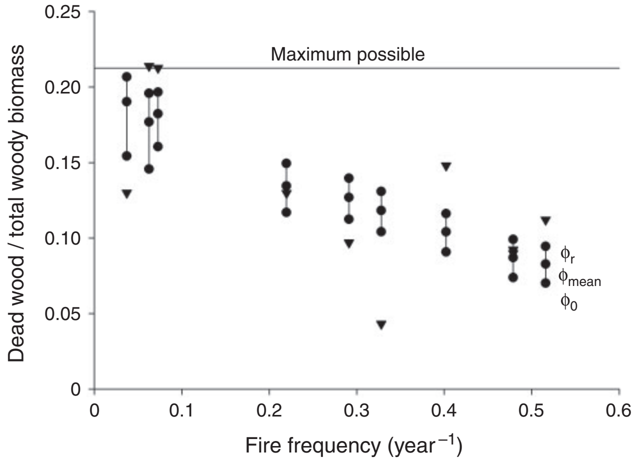

Fig. 8. Modelled (closed circles) and measured (closed inverted triangles) proportions of total aboveground woody biomass comprising dead wood. Modelled data are for the frequency of all fires and of early fires for the corresponding measured sites. The lower points are for the dead wood load immediately after the mean fire (Φ (0)); the mid points are for the mean dead wood load across space and time (Φ); and the upper points are at the time of the mean fire recurrence interval (Φr). The horizontal line represents the maximum possible proportion of dead wood in the absence of major disturbances, such as wind storms or drought.

carbon and emissions budgets. This ensured compliance with the 2006 guidelines for national greenhouse gas inventories (IPCC 2006). Regarding woody debris – important because of its biomass and high methane emission factors – the first step in this was the fitting of modified Olson curves to field observations. Fitting these curves supported estimates of carbon sequestration in new ERF methodologies and in the NIR. A further development has been the application of a mass balance approach to estimate the input parameters to the modified Olson curve from field data of tree stand structure, growth rates and woody combustion. These considerations allow the mortality rate of trees (and consequently the creation of dead wood) to be estimated. Across the whole savanna zone with more than 600 mm rainfall, more than 2% of trees die per year. Thus, in total, more than 400 million trees with a stem diameter ≥0.05 m and a total biomass of more than 72 Tg die per year. Previous estimates of greenhouse gas emissions from Australian savanna fires have not included standing dead trees. However, research from eucalypt woodlands in southern Queensland showed that they burn at rates similar to on-ground dead wood. New field data from semiarid savannas across northern Australia have confirmed that dead standing trees comprise most of the dead wood (Table 2). Further, the proportion of total woody biomass comprising dead wood increases with decreasing fire frequency and a decreasing proportion of late dry season fires. This gives scope for increasing the carbon stock in the woody debris pool with improved fire management. New parameters are presented for calculating woody debris dynamics, including dead trees, in Australia's savannas.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

This work was funded jointly by CSIRO, the National Environmental Science Program, Northern Australian Environmental Resources Hub and the Australian Department of the Environment and Energy. We thank Landgate for use of fire history data and Queensland Department of Agriculture and Fisheries for access to TRAPS woodland monitoring sites data.

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Appendix 1. Description of vegetation classes

These definitions are taken from Commonwealth of Australia (2018)

Vegetation fuel type code[A]	Vegetation fuel type name	Dominant strata: Strata	Dominant strata: Canopy height	Foliage projected cover	Characteristic descriptors: Grasses	Characteristic descriptors: Canopy trees	Characteristic descriptors: Shrubs	Characteristic descriptors: Substrates
hOFM	Open forest with mixed grasses	Canopy trees	Majority of trees >15 m	30–70%	Dominated by native perennial and annual tussock grasses	Various *Eucalyptus* and *Corymbia* species (for example, *E. tetrodonta, E. miniata, C. nesophila, C. stockeri*)	Various species – well developed shrub layer may or may not be present	Well drained deep soils, often sandy loams
hWMi	Woodland with mixed grasses	Canopy trees	Majority of trees >8 m	10–30%	Dominated by native perennial and annual tussock grasses; may be associated with hummock grasses (*Triodia* species)	Various *Eucalyptus* (for example, *E. tetrodonta*) and *Corymbia* spp, often with other taxa (for example, *Erythrophleum, Terminalia, Callitris*). May contain *Melaleuca*. spp.	Various species – well developed shrub layer may or may not be present	Various situations, from well-drained gravelly sites to those with impeded drainage
hWHu	Woodland with hummock grasses	Canopy trees	Majority of trees >8 m	10–30%	Dominated by hummock (*Triodia*) grasses. A mixture of native perennial and annual tussock grasses may also be present	Various *Eucalyptus* and *Corymbia* often with other taxa (for example, *Erythrophleum, Terminalia, Xanthostemon*) May contain *Melaleuca*. spp.	Various species – well developed shrub layer may or may not be present. Where present, may include woody heath taxa as listed for hSHH	Rocky shallow soils derived typically from sandstone (quartzite); also lateritic hills and plateau
hSHH	Shrubland (heath) with hummock grasses	Shrubs	Majority of shrubs <5 m	0–30%	The presence of hummock (*Triodia*) grasses, or other perennial members of the *Restionaceae* (*Lepyrodia, Dapsilanthus*), or sedges (*Schoenus sparteus*) or graminoids (for example, *Lomandra*, *Xanthorrhoea*)	Sparse trees	Conspicuous cover of heathy shrubs (for example, *Acacia*, *Calytrix*, *Grevillea*, *Hibbertia*, *Hibiscus, Jacksonia*, *Tephrosia*, *Verticordia*)	Shallow to rocky substrates derived typically from sandstone, metamorphosed sandstone (for example, quartzite), sometimes laterised; sand sheets
lWHu	Woodland with hummock grasses	Canopy trees	Majority of trees >10 m	10–30%	Hummock (Triodia) grasses usually dominant, tussock grasses may also occur	Various *Eucalyptus* and *Corymbia* often with other taxa (for example. *Erythrophleum*, *Terminalia*, *Xanthostemon*) May contain *Melaleuca* spp.	Well-developed shrub layer may/may not be present; may include woody heath taxa	Rocky shallow soils derived typically from sandstone (quartzite); also lateritic hills and plateau
lWMi	Woodland with mixed tussock/hummock grasses	Canopy trees	Majority of trees >10 m	10–30%	Dominated by native perennial and annual tussock grasses; may be associated with hummock (*Triodia*) grasses. May include limited areas of open forest with tussock/mixed grass	Various *Eucalyptus* (for example, *E. tetrodonta*) and *Corymbia* spp, often with other taxa (for example, *Erythrophleum*, *Terminalia*, *Callitris*) May contain *Melaleuca* spp.	Well-developed shrub layer may or may not be present.	Various situations including undulating to hilly land types on imperfectly to well drained soils

(*Continued*)

Appendix 1. (Continued)

Vegetation fuel type code[A]	Vegetation fuel type name	Dominant strata			Grasses	Characteristic descriptors		
		Strata	Canopy height	Foliage projected cover		Canopy trees	Shrubs	Substrates
lWTu	Woodland with tussock grasses	Canopy trees	Majority of trees >10 m	10–30%	Dominated by native perennial and annual tussock grasses	Various *Eucalyptus* (for example, *E. tectifica*) and *Corymbia* (for example, *C. opaca*) often with other taxa (for example, *Erythrophleum*, *Terminalia*) May contain *Melaleuca*. spp.	Well-developed shrub layer may or may not be present.	Majority deep well drained soils to those with impeded drainage, typically on flat to undulating land types with fertile volcanic-derived substrates
lOWM	Open woodland with mixed grasses	Canopy trees	Majority of trees <10 m	<10%	Dominated by hummock (*Triodia*) grasses, or codominant with tussock grasses	Various *Eucalyptus* and *Corymbia*, including *C. dichromophloia, E. leucophloia, E. brevifolia, E. pruinosa, E. tectifica*	Well-developed shrub layer may or may not be present. Where present, may include woody heath taxa	Shallow substrates on undulating stony rises and rocky hills
lSHH	Shrubland with hummock grasses	Shrubs	Majority of shrubs <5 m	<30%	Hummock (Triodia) grasses, and/or other perennial members of the Restionaceae (*Lepyrodia*, *Dapsilanthus*) sedges (*Schoenus sparteus*) or graminoids (for example, *Lomandra*, *Xanthorrhoea*)	Sparse trees. May include areas of low open *Melaleuca* hummock grassland	Conspicuous shrub (heath) layer, commonly Acacia species and various other taxa (for example, *Calytrix*, *Grevillea*, *Hibbertia*, *Hibiscus*, *Jacksonia*, *Tephrosia*, *Veritcordia*)	Sand plains often over laterite, or rocky, shallow substrates derived from sandstone

[A]Prefixes h and l indicate mean annual rainfalls of >1000 mm (high rainfall) and 600–1000 mm (semiarid) respectively.